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Spatial Pattern of Weeds Based on Multispecies Infestation Maps Created by Imagery

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Weeds are often spatially aggregated in maize fields, and the level of aggregation varies across and within fields. Several annual weed species are present in maize fields before postemergence herbicide application, and herbicides applied will control several species at a time. The goal of this study was to assess the spatial distribution of multispecies weed infestation in maize fields. Ground-based imagery was used to map weed infestations in rain-fed maize fields. Image segmentation was used to extract weed cover information from geocoded images, and an expert-based threshold of 0.102% weed cover was used to generate maps of weed presence/absence. From 19 site-years, 13 (68%) demonstrated a random spatial distribution, whereas six site-years demonstrated an aggregated spatial pattern of either monocotyledons, dicotyledons, or both groups. The results of this study indicated that monocotyledonous and dicotyledonous weed groups were not spatially segregated, but discriminating these weed groups slightly increased the chances of detecting an aggregated pattern. It was concluded that weeds were not always spatially aggregated in maize fields. These findings emphasize the need for techniques allowing the assessment of weed aggregation prior to conducting site-specific weed management.

Nomenclature: Bird vetch, *Vicia cracca* L. VICCR; broadleaf plantain, *Plantago major* L. PLAMA; common lambsquarters, *Chenopodium album* L. CHEAL; common ragweed, *Ambrosia artemisiifolia* L. AMBEL; dandelion, *Taraxacum officinale* G. H. Weber ex Wiggers TAROF; ladysthumb, *Polygonum persicaria* L. POLPE; oakleaf goosefoot, *Chenopodium glacum* L. CHEGL; oxeye daisy, *Chrysanthemum leucanthemun* L. CHYLE; redroot pigweed, *Amaranthus retroflexus* L. AMARE; rhombic copperleaf, *Acalypha rhomboidea* Raf. ACCRH; shepherd's purse, *Capsella bursa-pastoris* (L.) Medik. CAPBP; white clover, *Trifolium repens* L. TRFRE.

Key words: Dicotyledons, monocotyledons, site-specific weed management, spatial pattern, spatial segregation.

The spatial pattern of weeds in crop fields can be random or aggregated (Backes and Jacobi 2006; Heijting et al. 2007). The spatial distribution of weeds has consequences on the feasibility and profitability of implementing site-specific weed management (Cardina et al. 1997). If aggregated weed patterns are present and detected before or during herbicide application, this could lead to reductions in the area sprayed with herbicides (Timmermann et al. 2003). When weeds are randomly distributed, there is a reduced potential for herbicide savings and thus reduced opportunity for the recovery of the investment on spot-spraying equipment, especially if a buffer zone is used around sprayed areas (Barroso et al. 2004). Therefore, a better understanding of the spatial aggregation of weeds in a field could help better plan site-specific weed management and improve its potential economic benefits.

Several weed species are present in corn or maize (*Zea mays* L.) fields before herbicide application, and all these species can generate distinct seed dispersal and emergence patterns that overlap in fields. When considering an area covered with quadrats from which weeds are counted, a random spatial distribution is observed when the variance is equal to the mean density of weeds per quadrat (Fortin and Dale 2005; Greig-Smith 1983). When the variance is equal to the mean density of weeds per quadrat, this indicates that the weeds' spatial pattern follows a Poisson distribution and is neither underdispersed (patchy), nor overdispersed (regular) (Fortin and Dale 2005). Seed dispersal processes such as anemochory and recruitment from a randomly distributed seed bank can potentially

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generate random spatial patterns of weeds (Cardina et al. 1996). An aggregated spatial distribution is observed when the variance is higher than the mean density of weeds per quadrat (Fortin and Dale 2005). Multiple phenomena and processes can generate aggregated weed distributions. Barochorous (gravity) seed dispersal plays a major role in weed aggregation. Indeed, this is the most common weed dispersal strategy encountered in agricultural fields, and the expected range of dispersal is less than a few meters (Benvenuti 2007). Surface water runoff can also generate patches by carrying floating seeds such as those of *Polygonum* spp. and *Rumex* spp. to lower areas where they accumulate (Cavers and Harper 1967). Spatial variability in soil properties and fertility has also been shown to promote aggregated spatial patterns (Walter et al. 2002). Topography and soil texture were found to influence the spatial distribution of weeds in soybean [*Glycine max* (L.) Merr.] and maize fields (Dieleman et al. 2000).

Anthropomorphic factors and cropping operations can also influence the spatial distribution of weeds. The most important dispersal process is spread of crop residues and any weed seed in the field by the combine harvester (Barosso et al. 2006; Cousens and Woolcock 1997). Plowing and seedbed preparation can displace weed seed 2 to 15 m from initial position in one season (Marshall and Brain 1999). Furrow irrigation or wheel tracks can be more infested than undisturbed areas (Longchamps et al. 2012; Norsworthy et al. 2014; Tardif-Paradis et al. 2015). Most of these anthropomorphic phenomena generate weed patches that are elongated (anisothropy) in the direction of cultivation, as seen in maps presented in Longchamps et al. (2013) and in Norsworthy et al. (2014). Several factors thus affect the spatial distribution of weeds that can be random or aggregated, and the spatial patterns of the various weed species present in a field all contribute to the overall multispecies weed spatial pattern.

Statistical techniques have been developed to study the spatial distribution of point patterns. Although first-order statistics, such as the variance to mean ratio (VMR), only characterize the spatial distribution as being random, aggregated, or regular, second-order statistics measure the spatial intensity of the point pattern (Fortin and Dale 2005). Pielou's index of nonrandomness is a second-order statistic that uses (a) the estimate of the point density and (b) a sample of point-to-nearest-plant distance, to determine if a point pattern is aggregated and the intensity of aggregation (Pielou 1959). Pielou (1959) argued that this index outperformed other indices that use (a) the estimate of point density and (c) a sample of plant-to-nearest-plant distance because obtaining (c) is extremely laborious in practice compared to (b). A point-to-plant-based index also offers the theoretical advantage of encompassing multiple scales of patchiness as compared to a plant-to-plant index that only considers the smallest scale of aggregation (Greig-Smith 1983). Mountford (1961) argued that Pielou's index of nonrandomness accounts only for the variance of the point-to-plant distance and considers the variance of the estimate of point density to be zero, and thus suggested modifications to account for this error. However, when measuring the point density of an entire area rather than from randomly located quadrats, variance indeed equals zero. Pielou's index of nonrandomness is thus a suitable index to assess the spatial distribution of point patterns.

Growers have to control many species, either using a single nonselective herbicide (glyphosate or glufosinate) in herbicide-tolerant crops or a combination of herbicides (e.g., atrazine or bromoxynil + nicosulfuron) (Jhala et al. 2014), because a single selective herbicide will generally target either mostly grasses (monocotyledons) or broadleaf weeds (dicotyledons). Therefore, the spatial distribution of weeds in maize has to be assessed on a multispecies basis, but practical selective management options only separate monocotyledons from dicotyledons. Moreover, several weed-detection strategies such as image processing and fluorescence spectroscopy have failed to identify individual weed species while they succeeded in identifying weeds as monocotyledons or dicotyledons (Longchamps et al. 2012; Schuster et al. 2007).

Several papers have reported spatial aggregation of specific weed species (Heijting et al. 2007; Zanin et al. 1998). Other studies have separated weeds into two groups based on typical herbicide selectivity (i.e., monocotyledons or dicotyledons) to generate herbicide prescription maps that could reduce herbicide inputs (Nordmeyer 2006). It is of interest to determine if multispecies weed spatial distributions present a level of nonrandomness high enough for practical site-specific weed management (Jurado-Expósito et al. 2003). To better understand the spatial distribution pattern of multispecies weeds, it is also of interest to know if the monocotyledonous and dicotyledonous weed groups are spatially associated or if they are spatially

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segregated. If there was systematic association between monocotyledonous and dicotyledonous weed groups, there would be little incentive to separating these groups for site-specific weed management. The spatial segregation of plant species in natural ecosystems has been documented, but no literature exists on the spatial segregation of weed groups in crop fields (Bolker et al. 2003; Pacala 1997). The spatial segregation of plants has been studied at the root scale (Schenk et al. 1999) but has seldom been studied at the scale of 1 ha (Petit and Fried 2012).

The specific objectives of this study were to determine: (1) if aggregated spatial pattern of weeds can be detected without distinction of weeds species in maize fields dominated by annual weed species; (2) if monocotyledonous and dicotyledonous weed groups are spatially segregated; and (3) if the chances of detecting an aggregated pattern could be improved by separating monocotyledonous and dicotyledonous weed groups. This study was restricted to the spatial distribution of both annual (mostly) and perennial weed species germinating in the current year in conventionally-tilled maize fields.

Materials and Methods

Description of Study Sites and Field Selection. The data for this research were collected over the crop-growing seasons of 2008 and 2009 from June to July in 13 commercial maize fields. The 13 sites were located along the St. Lawrence River in the province of Quebec, Canada. Among the 13 fields, six were sampled both in 2008 and in 2009, for a total of 19 site-years. The fields were selected according to the following criteria: (1) maize was planted at 75-cm interrow spacing, (2) no mechanical weed control was implemented, (3) no residual herbicides were applied in the spring, and (4) conventional tillage with fall plowing and spring harrowing implements was used (no reduced or zero till). The crop rotation consisted of maize–soybean. Planters' width varied from one farm to the other and had four-, six- or eight-row units. Starter fertilizer containing nitrogen and phosphorous was applied uniformly in each field at levels prescribed by local crop advisors based on soil fertility and yield goals. Subsequent fertilizer applications were applied after data acquisition. Ground-based imagery of the fields was acquired 1 or 2 d prior to postemergence weed control, corresponding to the 2- to 4-leaf growth stage of maize.

For each site-year, a 1-ha field section was selected for ground-based imagery acquisition. The 1-ha field section was positioned away from the field margins and from common horsetail (*Equisetum arvense* L.) patches. Common horsetail patches were avoided because these perennial weeds form dense patches that are stable from year to year due to poor drainage conditions and tolerance to regular herbicide treatments (Goudy et al. 2001; Marshall et al. 1987). The focus of this study was on annual and perennial weed species germinating in the current year. The composition of the weed flora was evaluated at each site-year except site-year d08. Nine (in 2008) or 16 (in 2009) quadrats (0.5 m by 0.75 m) were systematically distributed throughout the 1-ha field sections. All weeds present in the quadrats were identified to the species level except monocotyledons (noted as Poaceae spp.) and counted.

Ground-Based Imagery and Segmentation of Vegetation. All 19 site-years were photographed with a Nikon D100 (Nikon, Melville, New York, NY) digital RGB camera mounted 2.5 m above the ground on a mobile platform covered with an opaque tarpaulin to remove sunlight. The images were acquired under high-intensity flash light (EL500 tubes, 5500 K CCT, Elinchrom, Renens, Switzerland) insuring controlled light conditions excluding sunlight. The camera was triggered every 3 m by a sensor on the wheel. Each image covered 2 m by 3 m of ground (resolution of about 1 pixel mm^{-2}) and was overlying four maize rows (Figure 1a). Around 1,100 images were taken in each site-year. Images thus acquired were analyzed with a custom-built program in Matlab™ version R2007b (The MathWorks, Inc., Natick, MA) to segment vegetation pixels from other pixels using principal component analysis applied on the whole RGB image (Figure 1a). One of the principal components isolated the vegetation. The first principal component (PC) segregated for the grey tarp on the sides of the image and the straw (light colors). Depending on the amount of vegetation pixels in the image, the second or the third PC segregated for the vegetation (Figure 1b), and the other PC segregated the soil. Images with vegetation pixels segmented from background (i.e., soil, residues, and grey tarp) were converted into binary images with "1" for vegetation and "0" for the rest. Details about the mobile platform and the image segmentation method can be found in Longchamps et al. (2013).

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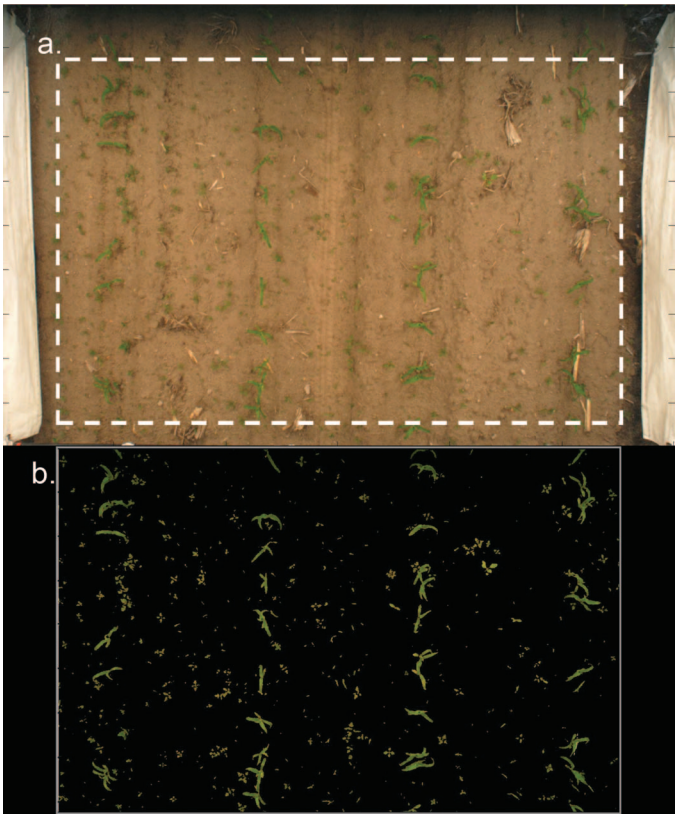


Figure 1. Example of (a) ground image acquired and (b) image where soil was removed using segmentation. The white dashed rectangle highlights the region of interest of the image. (Color for this figure is available in the online version of this article.)

Extraction of Weed Cover Information. Segmented binary images were processed to extract weed cover for each interrow area (Figure 1b). The first step consisted in computing a vertical (i.e., column-wise) sum of the pixel matrix (i.e., image). The vertical sum resulted in bell-shaped curves at the locations of the maize rows. Knowing the location of the center of the maize rows in the image, a maize row area was delineated by using a fixed distance on each side of the row center. This process generated three maize-free interrow areas of about 0.70 by 3 m for each image, considering that the crop row occupied about three 0.1 by 3 m areas. More details on image processing to extract weed cover information can be found in Longchamps et al. (2013). Weed cover was measured by summing the number of pixels of vegetation in the maize-free interrow areas divided by the total number of pixels for that area (i.e., one interrow of about 0.70 by 3 m). Weed cover was then converted to weed presence/absence using a weed cover threshold of 0.102% (Longchamps et al. 2014). Longchamps et al. (2014) determined this weed cover threshold by comparing the weed threshold of 2,795 images to the weed infestation assessment of each image by three independent crop advisors specialized in maize production. The centroid of each interrow area where weeds were considered present (i.e., weed cover above threshold) was geocoded and will be referred to as "point" in further sections. Maps of points indicating presence of weeds will be referred to as "multispecies weed maps" for the scope of this paper.

Crop Advisor Input for Weed Groups. A sample of images was sent to three crop advisors specialized in maize production for the evaluation of weed infestation. All three are accredited agronomists. A total of 2,795 images were selected from the entire data set, consisting of about one for every 10 images. The 2,795 selected images were sent to the crop advisors along with a custom-built executable Matlab program with a graphical user interface to process the images. Advisors had to classify each image with the following classes: (0) not infested, (1) dominated by monocotyledons, (2) equal proportions of monocotyledons and dicotyledons, or (3) dominated by dicotyledons. To determine the group of weed (monocotyledons or dicotyledons) in each image, a compilation was done in order to integrate the judgment of all three crop advisors into a single value. Table 1 shows all possible classification scenarios by the three advisors encountered over the 2,795-image assessment and the resulting output, and also indicates how each possible scenario is handled. In the cases of ambivalence in expert evaluation (Cases 6 and 9 in Table 1), the image was further investigated by the authors of this paper to confirm the type of infestation. To do so, the image was magnified and carefully inspected and rated as 0, 1, 2, or 3, according to this in-depth inspection. A total of 109 (about 4%) images required such further investigation. With a single value depicting the weed composition (i.e., 0, 1, 2, or 3) of each of the 2,795 images (about 147 site-year^{-1}) and the geocoordinates of each image, it was possible to create a map of monocotyledons (i.e., images ranked as 1 or 2) and a map of dicotyledons (i.e., images ranked as 2 or 3) for each site-year. The resulting dataset consisted of maps (point patterns) of the presence of monocotyledons and maps of the presence of dicotyledons, and this dataset will be referred to as "maps of weed groups" for the scope of this paper.

Data Analysis. *Detection of Aggregated Pattern in Multispecies Weed Maps.* The first set of analyses

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Table 1. Final classification of images by weed group based on the domination of one group as assessed by three crop advisors for every combination of advisor classification. Weed cover was judged to be: too low to be dominated by a given weed group (0), dominated by monocotyledons (1), composed of relatively equal proportions of each group (2), or dominated by dicotyledons (3). Some images required further evaluation by the authors (9).

Case	Advisor 1	Advisor 2	Advisor 3	Final classification
1	0	0	0	0
2	0	0	1[a]	1
3	0	0	2	2
4	0	0	3	3
5	0	1	1	1
6	0	1	2	9
7	0	1	3	2
8	0	2	2	2
9	0	2	3	9
10	0	3	3	3
11	1	1	1	1
12	1	1	2	1
13	1	1	3	2
14	1	2	2	2
15	1	2	3	2
16	1	3	3	2
17	2	2	2	2
18	2	2	3	2
19	2	3	3	3
20	3	3	3	3

[a] The position of the numbers is interchangeable among the three advisors. For instance, in Case 2, the 1 could have been under any of the three advisors and the final classification would have been the same.

consisted of calculating Pielou's index of nonrandomness (Pielou 1959) on multispecies weed maps to determine if the spatial distribution of weeds was aggregated, random, or regular for each site-year. Pielou's index of nonrandomness (I) assesses the spatial pattern of a point pattern with Equation 1:

$$I = \pi D \omega \quad [1]$$

where D is an estimate of the density (i.e., number of points where weed cover was above threshold divided by the map area of about 1 ha) and ω is the mean of the squares of the distances between randomly located control points and their nearest neighboring object on the map (i.e., centroid of an interrow [crop-free sections in the image] where weed cover is above threshold; Pielou 1959). For each site-year, 100 control points were randomly distributed within the boundaries of the weed map to measure Pielou's index of nonrandomness. The distribution of weeds follows a regular pattern if I is significantly smaller than one, and follows an aggregated pattern if I is significantly larger than one. Otherwise, the point pattern is considered to be randomly distributed. Because the position of the weed points were forced to be in the mapped locations (three points, 0.75 m apart perpendicular to the rows and about 2 m apart along the row; see Figure 2), a permutation test was computed in order to get a confidence interval adapted to this particular situation. The significance of the resulting index was verified by a permutation test based on 1,000 permutations of both weed presence or absence criteria and control point locations. The weed permutations were done by allocating zeros (absence) and ones (presence) randomly across the sampled locations in the same proportions as the tested point pattern. The lower and upper limits of the interval were 2.5% and 97.5% respectively. Pielou's index of nonrandomness and permutation tests were computed using a custom-built R code (R Development Core Team 2012).

Assessment of Spatial Segregation for the Maps of Weed Groups. The spatial segregation between monocotyledonous and dicotyledonous weed groups using Pielou's index of segregation was applied to maps of weed groups (Pielou 1961). This index describes two point patterns as being spatially associated, randomly associated, or spatially segregated. Pielou's index of segregation (S) is calculated using Equation 2:

$$S = 1 - \frac{\text{Observed number of AB and BA nearest neighbor relationship}}{\text{Expected number of AB and BA nearest neighbor relationship}} \quad [2]$$

where AB is the frequency of point A (i.e., dicotyledon points) having B (i.e., monocotyledon point) as a nearest neighbor, and BA is the frequency of point B having A as a nearest neighbor. The numbers of AB and BA are obtained by creating a 2 by 2 contingency table of the base points to their corresponding nearest neighbor. A Pielou's index of segregation significantly larger than zero indicates spatial segregation between the two point patterns. Points for which the nearest neighbor was a mixed point (where the infestation was from a mix of both weed groups) formed both a matching pair and a mixed pair with its nearest neighbor. As suggested by Meagher and Burdick (1980), a Monte Carlo procedure with 1,000 permutations was computed to test for the significance of Pielou's index of segregation ($\alpha = 0.05$). Again, the permutations were done by allocating zeros (e.g., absence of monocotyledons)

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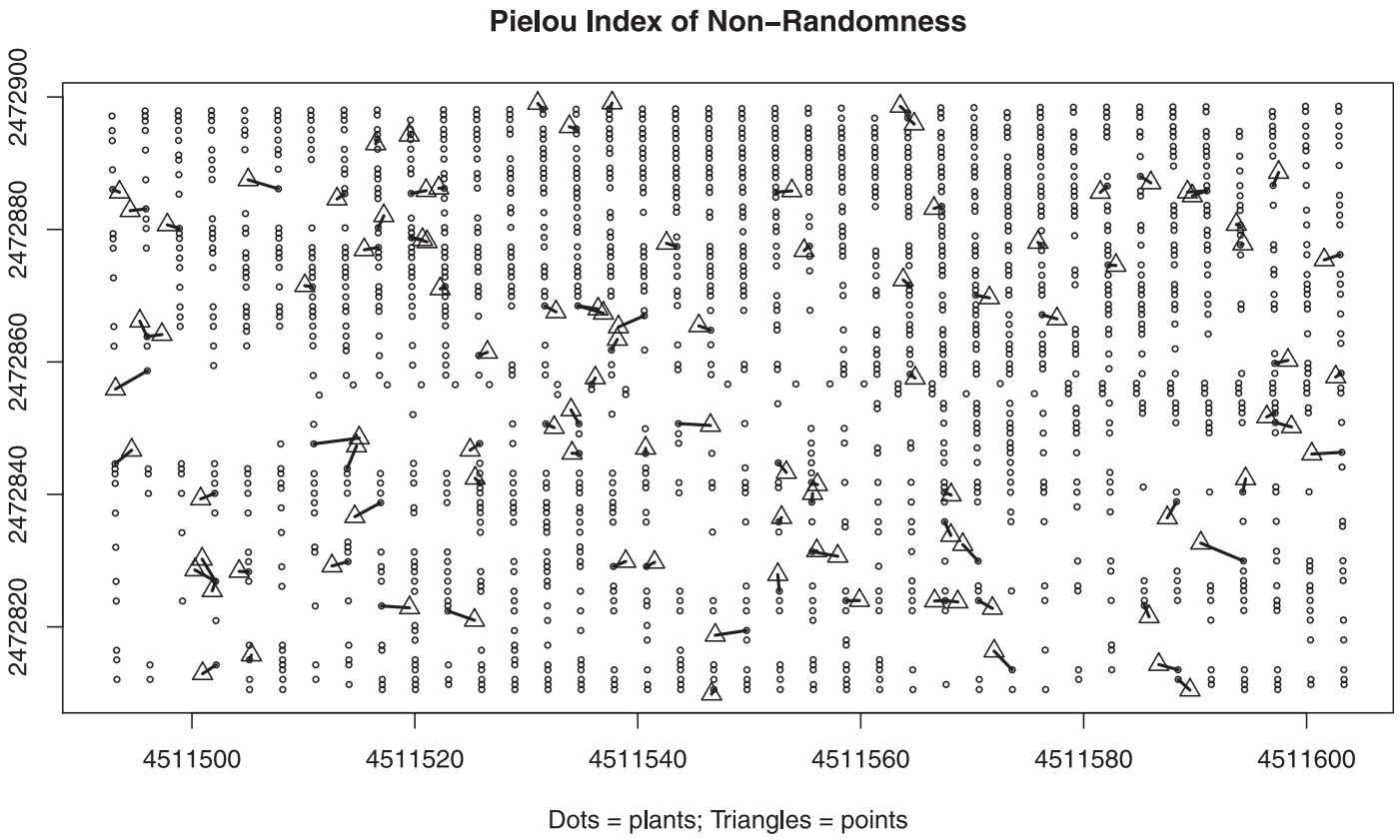


Figure 2. Map of weed presence showing points where weeds were present based on the weed threshold (○), and randomly allocated control points (Δ) with their link (–) to their nearest-neighboring weed point.

and ones (e.g., presence of monocotyledons) randomly across the sampled locations in the same proportions as the tested point patterns. Pielou's index of segregation and the Monte Carlo procedure were implemented with the statistical software R (R Development Core Team 2012) with custom code.

Spatial Pattern across Weed Groups. The third objective of this study was to observe the number of site-years (i.e., multispecies weed maps) showing an aggregated pattern and to verify if considering only the monocotyledonous weed group or only the dicotyledonous weed group would increase the number of site-years showing an aggregated pattern. For this section, the VMR was used to assess the spatial pattern of the three different maps using the "maps of weed groups": only monocotyledons, only dicotyledons, and both monocotyledons and dicotyledons maps merged. Each map of each site-year was divided into quadrats of equal dimensions (see below) and the occurrence of either monocotyledons, dicotyledons, or both weed groups together within each quadrat was counted. The number of occurrences within each quadrat was computed with the function "quadratcount" from the "spatstat" package (Baddeley and Turner 2005) in the statistical software R (R Development Core Team 2012). The VMR was calculated by dividing the variance of point counts across the quadrats by the average number of points across the quadrats. The statistical significance of VMR was assessed using a chi-squared test ($\alpha = 0.05$; Cuzick and Edwards 1990) with the function "pchisq.test" from "stats" package of the statistical software R (R Development Core Team 2012). A VMR significantly lower than one indicates a regular point pattern, whereas a VMR significantly higher than 1 indicates an aggregated point pattern. If the VMR was not significantly different from one, the pattern was considered as being randomly distributed.

The size and shape of the quadrats used has an effect on the VMR (McGrew et al. 2000). Four different quadrat dimensions were compared to run the analysis. The first quadrat size was based on the apparent (i.e., visual observation of the weed maps) dimensions of monocotyledons clusters and was variable from one site-year to the other. The second quadrat size was based on the apparent dimensions of dicotyledons clusters and was variable from one site-year to the other. The third quadrat size was an

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Table 2. Density in plants m^{-2} of the main weed species for each site-year. Overall (including all species) plant density is indicated in the last column on the right.

Site-year	Poaceae spp.[a]	CHEAL[b]	CAPBP	TRFRE	AMBEL	CHEGL	AMARE	TAROF	POLPE	VICCR	ACCRH	Overall
a08	4.7	5.3	0.3	3.6	—[c]	—	—	4.7	—	—	—	19.3
a09	22.0	8.7	21.3	9.3	—	—	7.3	4.8	1.0	0.2	—	79.8
b08	4.4	0.6	—	—	—	—	—	—	1.5	0.3	3.3	10.1
c09	2.7	1.8	1.8	0.7	—	—	—	—	—	—	0.2	34.7
d08	No data available for this site-year											
d09	19.3	2.7	0.2	0.7	0.2	—	—	0.5	0.2	0.2	0.2	28.2
e08	395.6	27.0	0.3	—	—	—	9.2	3.0	—	4.7	—	439.7
e09	123.5	24.5	0.7	—	0.2	—	2.2	—	—	1.0	—	153.2
f08	13.3	4.7	0.3	3.9	0.6	—	0.9	—	—	—	—	25.2
f09	13.0	2.3	0.3	2.7	—	—	—	2.2	—	—	0.5	25.2
g08	79.5	2.7	0.3	9.5	24.3	—	—	—	5.4	—	—	128.0
h09	6.7	8.3	0.2	0.2	—	—	1.0	—	—	—	0.8	17.8
i09	8.2	1.0	—	—	0.5	—	—	—	—	—	0.2	11.0
j08	1.2	3.6	37.9	1.2	—	—	0.3	—	—	—	—	44.1
j09	2.0	4.7	6.3	0.2	—	—	—	—	—	—	—	13.3
k09	0.8	0.8	7.2	0.5	—	—	—	0.2	—	—	—	9.8
l08	0.9	17.8	3.6	2.7	—	—	—	1.5	—	—	—	27.0
l09	3.8	6.5	1.5	7.7	—	0.3	—	1.7	0.2	—	0.2	31.8
m08	2.1	—	—	—	—	24.3	2.4	-	—	—	—	48.9

[a] Poaceae species were not distinguished at the genus and species level and were all categorized as Poaceae spp. in the survey.

[b] Abbreviations (Bayer codes for weed species): AMARE, redroot pigweed, *Amaranthus retroflexus*; AMBEL, common ragweed, *Ambrosia artemisiifolia*; ACCRH, rhombic copperleaf, *Acalypha rhomboidea*; CAPBP, shepherd's purse, *Capsella bursa-pastoris*; CHEAL, common lambsquarters, *Chenopodium album*; CHEGL, oakleaf goosefoot, *Chenopodium glacum*; POLPE, ladysthumb, *Polygonum persicaria*; TAROF, dandelion, *Taraxacum officinale*; TRFRE, white clover, *Trifolium repens*; VICCR. bird vetch, *Vicia cracca*.

[c] Species not observed in that field.

average of all quadrat dimensions previously mentioned and was the same for all site-years. The fourth quadrat size was based on a realistic spray boom section swath (6 m or 8 maize rows) and was the same for all site-years. Apparent anisotropy was taken into account to determine the quadrat shape (i.e., quadrats elongated along the maize rows) using a ratio of 1 : 2 (width : length) for all quadrats. Upon VMR analysis, the maps were characterized as being aggregated if any of the quadrat dimensions yielded an aggregated pattern. Thus, for each site-year and for the three infestation types (i.e., dicotyledons, monocotyledons, or multispecies) the spatial process was characterized as aggregated or not.

Results and Discussion

Composition of Weed Groups and Quadrat Dimensions. Grasses (Poaceae spp.) and common lambsquarters were the most commonly observed weed species/groups (Table 2). Although grasses were not recorded at the species level, they were generally composed of common weed species such as quackgrass [*Elymus repens* (L.) Gould], yellow foxtail [*Setaria pumila* (Poir.) Roemer & J.A. Schultes], and barnyardgrass [*Echinochloa crus-galli* (L.) Beauv]. Common lambsquarters is widespread in Canada and in the United States and is considered as one of the most common and problematic weed species in the world (Bassett and Crompton 1978; Efloras 2015; USDA–NRCS 2010). It is thus considered that the weed species composition of the site-years in this study was not uncommon and was representative of maize fields' flora. It is well documented that all weed species do not have the same level of competitiveness with the crop (Zimdahl 2004). Although some weed species are clearly more competitive than others, distinguishing individual species using image analysis is difficult and not very useful unless a species poses a particular threat (e.g., is glyphosate resistant) and has to be controlled separately.

Quadrat dimensions used to calculate the VMR ranged from 10 m to 40 m wide by 20 m to 60 m long for both monocotyledons and dicotyledons. Quadrats had a total area ranging from 200 m^2 to 2,400 m^2. Anisotropy was not tested for, but was visually apparent when patches were discernible

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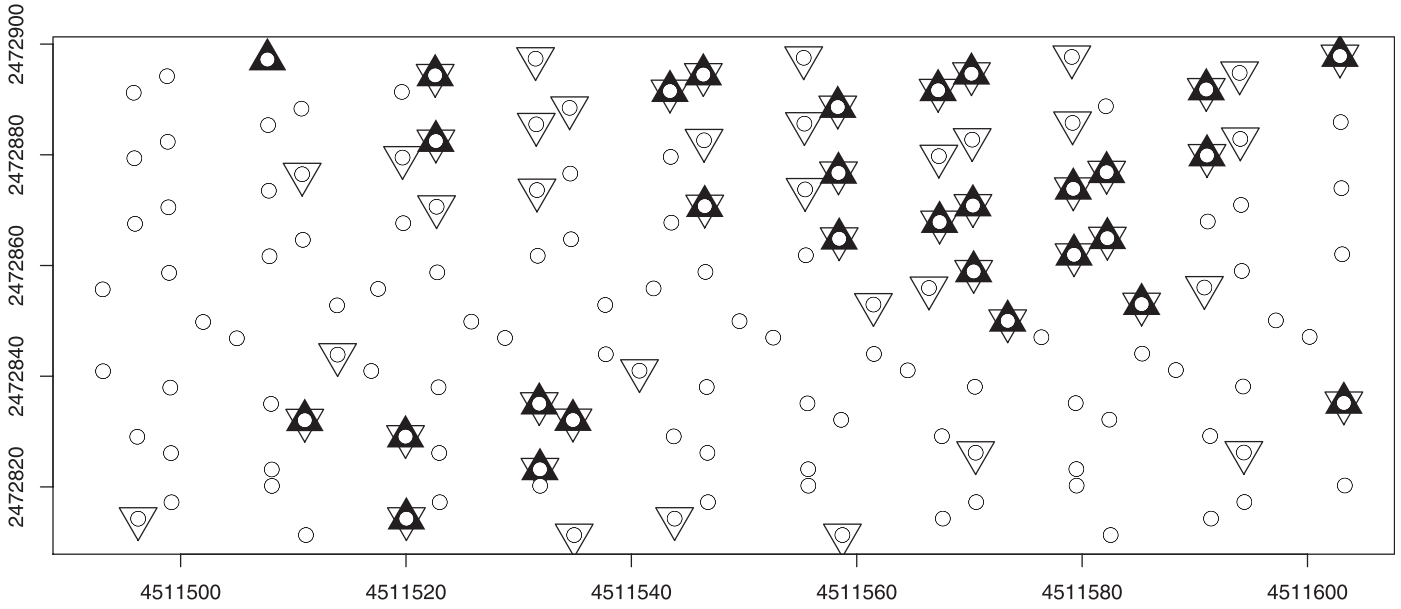


Figure 3. Illustration of quadrat divisions showing all sampled points (○), points with weed cover above threshold for which the weed group was assessed as monocotyledons (▲), points with weed cover above threshold for which the weed group was assessed as dicotyledons (▽). Mixed points form stars with both triangles overlapping.

with the naked eye (see patches created by ▲ and ▽ symbols in Figure 3). These quadrat sizes were linked to the range of weed patches visible on the maps and were consistent with the observations of Johnson et al. (1996) that detected a range of 25 m perpendicular to crop rows and 45 m along rows for velvetleaf (*Abutilon theophrasti* Medik.) and 20 to 50 m perpendicular to crop rows for 60 to 80 m along rows for common sunflower (*Helianthus annuus* L.), two dicotyledonous species. Zanin et al. (1998) reported a range of 14 m for common purslane (*Portulaca oleracea* L.) and 40 m for pigweeds (*Amaranthus* spp.), all dicotyledons, with elongation in the direction of crop rows. Other studies have used a square grid size linked to the width of a spray boom as reported by Gerhards and Christensen (2003). Therefore, the choice of the spatial analysis technique and the different quadrat dimensions used for this analysis were consistent with information from the literature. Moreover, based on the VMR calculation of all sample points, no aggregated pattern was identified for the 76 combinations of site-year and quadrat dimensions, confirming the independence between the sample point locations and the eventual detection of an aggregated pattern.

Relationship between Multispecies Weed Patterns and Weed Groups. According to Pielou's index of nonrandomness, there was a significant aggregated point pattern in six of 19 (32%) site-years and only one (f08) showed a significant regular point pattern ($\alpha = 0.05$). The remaining 12 site-years demonstrated a spatial distribution not significantly different from random (Table 3).

Several studies based on individual weed species depict aggregated patterns (Cardina et al. 1996; Dieleman and Mortensen 1999; Gonzalez-Andujar and Saavedra 2003) but few studies have compared multispecies weed patterns (Jurado-Expósito et al.

Table 3. Pielou's index of nonrandomness based on exhaustive maps of weed presence for each site-year, along with the resulting spatial pattern.

Site-year	Pielou's index	Spatial pattern
a08	1.44**	Aggregated
b08	2.66**	Aggregated
d08	0.87	Random
e08	0.88	Random
f08	0.79*	Regular
g08	0.94	Random
j08	1.17	Random
l08	1.27*	Aggregated
m08	0.83	Random
a09	0.99	Random
c09	0.82	Random
d09	1.79**	Aggregated
e09	0.93	Random
f09	1.09	Random
h09	2.84**	Aggregated
i09	1.21*	Aggregated
j09	0.91	Random
k09	1.09	Random
l09	0.89	Random

* $P < 0.05$; ** $P < 0.001$.

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Table 4. Pielou's index of segregation, confidence limits (Lower limit [LL] 2.5% and upper limit [UL] 97.5%) of the confidence interval, and proportion of monocotyledons based on weed counts, for each site-year as measured by crop advisors on sampled images. Pielou's index of segregation outside the confidence limit would indicate significant segregation in point patterns.

Site-year	Pielou's index of segregation	LL 2.5%	UL 97.5%	Percentage of monocotyledons[a]
a08	0.02	−0.29	0.31	34
b08	0.03	−0.47	0.43	47
d08	0.01	−0.17	0.16	47
e08	−0.01	−0.17	0.17	59
f08	0.01	−0.18	0.20	23
g08	−0.01	−0.16	0.16	41
j08	−0.01	−0.07	0.27	08
l08	0.00	−0.05	0.42	04
m08	0.00	−0.15	0.34	07
a09	−0.05	−0.24	0.24	22
c09	0.01	−0.16	0.18	62
d09	0.00	−0.52	0.43	44
e09	0.01	−0.19	0.18	44
f09	−0.06	−0.21	0.20	38
h09	0.02	−0.26	0.27	31
i09	0.03	−0.32	0.34	36
j09	0.00	−0.09	0.22	07
k09	0.00	−0.09	0.25	08
l09	0.00	−0.01	0.00	01

[a] Proportion based on image evaluation by crop advisor. The percentage of dicotyledons can be inferred by the difference between 100 and the percentage of monocotyledons.

2003). Spatial aggregation evaluations in the present study indicate that herbicide savings from spot-spraying could be foreseen in only a third of fields. This is consistent with observations from Jurado-Exposito et al. (2003) who observed 61% reduction in herbicide use in cultivated sunflower (*Helianthus annuus* L.) at one location where the spatial structure of multispecies weeds was moderate, but at another location where the spatial structure of multispecies weeds was weak, the herbicide reduction was only 1%.

Spatial Segregation between Monocotyledonous and Dicotyledonous Weed Groups. In the present study, no site-year showed segregation between the two groups of weeds at the scale of 1 ha, i.e., having an index significantly larger than zero (Table 4 and Figure 3). The confidence interval, as estimated from 1,000 permutations, was almost symmetrical around zero except for site-years that had less than 12% of monocotyledons (Table 4). This absence of segregation between weed groups in conventionally tilled maize fields could be explained by the mixing of the seed bank by plowing operations that displace weed seeds of all species both vertically and laterally in the seed bank (Colbach et al. 2000). However, absence of systematic association between these weed groups suggests that it might be beneficial to distinguish between them to increase the odds of finding an aggregated pattern because the spatial distribution of monocotyledons and dicotyledons was not necessarily the same.

Table 5. Spatial distribution of monocotyledons, dicotyledons, and multispecies (all weeds), based on four quadrat dimensions for site-years where an aggregated pattern was detected using variance-to-mean analysis. Spatial distributions were either aggregated (AGG) or not aggregated.

Site-year	Point process		
	Dicotyledonous	Monocotyledons	Multispecies
a08	AGG		AGG
d08	AGG	AGG	AGG
l08	AGG		AGG
m08		AGG	
f09		AGG	
h09	AGG		AGG

Spatial Pattern across Weed Groups. The results of the quadrat analysis demonstrated that point patterns containing both weed groups, only monocotyledons, or only dicotyledons presented different spatial distributions. From the 19 site-years, one had all three point patterns aggregated and 13 (68% of the site-years) had none of the three point patterns aggregated. In 74% of the site-years, all three point patterns displayed the same spatial distribution (i.e., all three random or all three aggregated). However, aggregated patterns are the ones that matter for the implementation of site-specific weed management. Six site-years (i.e., 32% of the site-years) had at least one weed group showing an aggregated pattern (Table 5). For only one site-year (i.e., 5% of the site-years), the spatial pattern of monocotyledons, dicotyledons, and multispecies showed an aggregated pattern. Based on the results showed in Table 5, if it was not possible to discriminate between monocotyledonous and dicotyledonous weed groups, only four site-years would be considered as aggregated as compared to six when weed group discrimination is possible. A similar situation was observed by Jurado-Expósito et al. (2003), where the spatial pattern of multispecies infestation was weaker than the spatial pattern of individual species. Hamouz et al. (2004) and Wiles et al. (1992) also reported a patchiness index for multispecies weed infestation systematically lower than the patchiness index for

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individual species. When aggregated patterns were only observed in one or two groups, the multispecies point pattern and the dicotyledons point pattern were both aggregated, whereas the monocotyledons point pattern was not, and when the monocotyledons point pattern was aggregated, the other two point patterns were not (Table 4). This could be explained by dicotyledonous weeds being generally more abundant than grasses (Table 4). The only site-year where all groups were aggregated had relatively equal proportions of monocotyledons and dicotyledons, 47 and 53%, respectively. It appears that detecting weeds without prior knowledge of species could lead to the detection of some level of aggregation possibly suitable for spot-spraying. However, discriminating between monocotyledonous and dicotyledonous weed groups slightly increased (by about 10% more) the chances of detecting aggregated weed patterns, even when the multispecies spatial distribution was not aggregated.

Our findings suggest that sensing weed cover at a scale of 6 m^2 (one image in our experiment) in rainfed maize fields dominated by annual weeds would reveal a random distribution of weeds in the majority (68%) of fields and thus lead to limited potential benefits for site-specific weed management. Several studies have reported a large range in the saving potential associated with site-specific weed management across fields (EWRS–SSWM 2005; Gerhards and Oebel 2006). Two potential conclusions could be drawn from these observations. The first implies the scale at which the weeds are detected and controlled. In theory, one can assume that the finer the resolution of detection and control of weeds, the higher the potential savings on herbicides, because weeds do not occupy the entire space left by the crop. Before herbicide application, there is a great likelihood of finding weeds in a 1-ha quadrat, whereas in a 1 cm^2 quadrat, chances are high that no weeds will be detected. The detection scale used in the present study is consistent with the equipment currently used by farmers in commercial fields. However, the possibility to detect and control weeds at the cm scale has been demonstrated, and this kind of technology can potentially be used in the future (Slaughter et al. 2008). Another conclusion that can be drawn is the necessity to have an evaluation of the field prior to implementing site-specific weed management. There is a cost to site-specific weed management, and if weeds are distributed randomly across a field, the extra cost increases the chances of applying weed control on a large proportion of the field and reduces the chances of a positive net return (Barroso et al. 2004). These conclusions are based on multispecies weed mapping and outcomes could have been different if individual species had been mapped. Multispecies weed maps are consistent with common weed control practices that rarely target individual species. As practices evolve, it is possible that individual species will be targeted by farmers (e.g., resistant weed species). In this case, more powerful image analysis and mapping techniques will be required for studying individual weed species at a finer resolution with an intense sampling plan.

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